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METHOD AND APPARATUS FOR INTERROGATING FIBER OPTIC SENSORS

BACKGROUND OF THE INVENTION

1. Technical Field

This invention relates to fluid flow sensing devices that use fiber optics and more particularly to those devices that measure the pressure variations within the pipe.

2. Background Information

In the petroleum industry, there is considerable value in the ability to monitor the flow of petroleum products in the production pipe of a well in real time. Historically, flow parameters such as the bulk velocity of a fluid have been sensed with venturi type devices directly disposed within the fluid flow. These type devices have several drawbacks including the fact that they provide an undesirable flow impediment, are subject to the hostile environment within the pipe, and typically provide undesirable potential leak paths into or out of the pipe. In addition, these type devices are also only able to provide information relating to the bulk fluid flow and are therefore unable to provide information specific to constituents within a multi-phase flow.

Some techniques utilize the speed of sound to determine various parameters of the fluid flow within a pipe. One technique measures the amount of time it takes for sound signals to travel back and forth between ultrasonic acoustic transmitters/receivers (transceivers). This is sometimes referred to a "sing-around" or "transit time" method. United States Patent numbers 4,080,837, 4,114,439, 5,115,670 disclose variations of this method. A disadvantage of this type of technique is that gas bubbles and/or particulates in the fluid flow can interfere with the signals traveling back and forth between the transceivers. Another disadvantage of this type of technique is that it considers only the fluid disposed between transceivers during the signal transit time. Fluid flow within a well will very often be non-homogeneous, for example containing localized concentration variations ("slugs") of water or oil. Localized concentration variations can affect the accuracy of the data collected.

One prior art technique of sensing a parameter within a body is disclosed in US Patent 4,950,883 to Glenn wherein a broadband source is used in cooperation with a fabry-perot resonator sensor. The high reflectivity gratings establish a resonant signal, the wavelength of which is indicative of the parameter of interest of a fluid within the body. Among other short comings, this prior art method has limited usefulness in a downhole environment for several reasons such as the limited resolution and relatively slow update rates.

Multiphase flow meters can be used to measure the flow rates of individual constituents within a fluid flow (e.g., a mixture of oil, gas, and water) without requiring separation of the constituents. Most of the multiphase flow meters that are currently available, however, are designed for use at the wellhead or platform. A problem with utilizing a flow meter at the wellhead of a multiple source well is that the fluid flow reaching the flow meter is a mixture of the fluids from the various sources disposed at different positions within the well. So although the multiphase meter provides the advantage of providing information specific to individual constituents within a fluid flow (which is an improvement over a bulk flow sensors), the information they provide is still limited because there is no way to distinguish sources.

Acquiring reliable, accurate fluid flow data downhole at a particular source environment is a technical challenge for at least the following reasons. First, fluid flow within a production pipe is hostile to sensors in direct contact with the fluid flow. Fluids within the production pipe can erode, corrode, wear, and otherwise compromise sensors disposed in direct contact with the fluid flow. In addition, the hole or port through which the sensor makes direct contact, or through which a cable is run, is a potential leak site. There is great advantage in preventing fluid leakage out of the production pipe. Second, the environment in most wells is harsh, characterized by extreme temperatures, pressures, and debris. Extreme temperatures can disable and limit the life of electronic components. Sensors disposed outside of the production pipe may also be subject to environmental materials such as water (fresh or salt), steam, mud, sand, etc. Third, the well environment makes it difficult and expensive to access most sensors once they have been installed and positioned downhole.

What is needed, therefore, is a reliable, accurate, and robust apparatus for interrogating fiber optic sensors coupled to a pipe, one that can determine minute sensor response to a fluid flow within a pipe, one that enables a high update rate, and one that is operable in an environment characterized by long optical cable lengths.

SUMMARY OF THE INVENTION

It is, therefore, an object of the present invention to provide a method and apparatus for interrogating fiber optic sensors sensing at least one parameter of the fluid flow within a pipe that is reliable, accurate, that can determine minute sensor response to a fluid flow within a pipe, that enables a high update rate, and that operates in a in an environment characterized by long transmission lengths and high temperatures and pressures.

According to the present invention, an apparatus for interrogating fiber optic sensors that are coupled to a pipe for non-intrusively sensing fluid flow within the pipe is provided. The apparatus includes a narrow band optical source producing a series of discrete pulses of narrow band light, a coupler to split the pulses into first and second pulses, a modulation device to impress a modulation carrier onto the first pulses, a time delay coil delaying the second pulses by a known amount of time, a coupler to recombine the pulses onto a single optical fiber, a first reflective grating positioned on one side of the sensor and a second reflective grating positioned on the opposite side of the sensor, an optical circulator to direct the pulses to a photo receiver to receive reflected pulses from the gratings, and an interrogator to compare the pulses. The present invention further includes the capability to interrogate a plurality of sensors along a single optical fiber string with each sensor positioned between a pair of reflective gratings.

The interrogator compares the phase shift between the reflected first pulses from the second grating with the reflected second pulses from the first grating to determine a change in magnitude of the measured parameter.

The narrow band light source emits pulses at a time interval between successive pulses that is short enough in duration to extract meaningful information from the sensors. At the same time the interval between successive

pulses is long enough to allow the reflected pulses to be properly distinguished. The time delay coil is advantageously sized to match the nominal length of the sensor. The reflected pulses will establish an interference pattern at the optical receiver, the intensity of which is based on the phase shift produced by the change in length of the sensor, indicative of the magnitude of the sensed parameter.

An advantage of the present invention apparatus is that it enables long transmission lengths of optical fiber between the source and the sensors based on low loss elements and low reflectivity gratings. As a result sensors may be placed at remote locations from instrumentation without the need for optical amplifiers.

Another advantage of the present invention is the ability multiplex a plurality of sensors, each having a pair of gratings that reflect a single nominal wavelength. As a result a plurality of sensors may be positioned along a single optical fiber. This enables a system that is insensitive to cross-talk, reduces optical fiber and equipment requirements, and permits installation in size limited applications.

The foregoing and other objects, features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG.1 is a diagrammatic view of a well having a casing and a pipe, and present invention flow meters positioned at various locations along the pipe inside the casing.

FIG.2 is a diagrammatic view of an exemplary embodiment of the present invention apparatus for non-intrusively measuring fluid flow parameters within a pipe.

FIG.3 is a diagrammatic view of an embodiment of a sensing device within the present invention.

FIG.4 is a diagrammatic view of an embodiment of a sensing device within the present invention.

FIG.5 is a diagrammatic view of an embodiment of a sensing device within the present invention.

FIG. 6 is a block diagram of an instrument and apparatus for non-intrusively measuring fluid flow parameters within a pipe.

FIG. 7 is a graphical representation of reflected pulses from the various gratings of the sensing device of the present invention.

FIG. 8 is a graphical representation of the interference patterns of the reflected pulses shown in FIG. 7.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. 1 there is shown an intelligent oil well system 10 containing one or more production pipes 12 that extend downward through a casing 14 to one or more petroleum sources 16. An annulus 18 is formed between the pipe 12 and the casing 14. Each production pipe 12 may include one or more lateral sections that branch off to access different petroleum sources 16 or different areas of the same petroleum source 16. Fluid mixtures flow from the sources 16 to the platform 20 through the production pipes 12. The fluid mixtures consist predominantly of petroleum products and water. The production pipe 12 includes one or more the present invention apparatus 22 for non-intrusively sensing fluid flow within a pipe (also referred to hereinafter as a "flow meter") to monitor various physical parameters of the fluid mixtures as they flow through the production pipes 12.

The present invention flow meter 22 includes a first sensing array 24 for sensing acoustic signals traveling at the speed of sound (SOS) through the fluid within the pipe 12 (hereinafter also referred to as the "SOS sensing array"), a second sensing array 26 for sensing short duration local pressure variations traveling with the fluid flow (hereinafter also referred to as the "flow velocity sensing array"), and a housing 28 attached to the pipe 12 for enclosing the sensing arrays 24,26. Each flow meter 22 can be incorporated into an existing section of production pipe 12, or can be incorporated into a specific pipe section that is inserted in line into the production pipe 12. The distributed scheme of flow meters 22 shown in FIG.1 permits an operator of the intelligent well system 10 to determine the extent and location of breakthrough of water into the

petroleum reserve. The availability of this type of information permits the user to monitor and intelligently control the production of the petroleum reserve.

The sensing arrays 24,26 receive optical power and produce optical signals via fiber optic cables 30 that extend between the flow meter 22 and instrumentation 100 (FIG. 6) residing on the platform 20 or at a remote location in communication with the platform 20. Optical fiber pressure sensors 32 within each sensing array 24,26 may be connected individually to the platform instrumentation, or may be multiplexed along one or more optical fibers using known techniques including, but not limited to, wavelength division multiplexing (WDM) and time division multiplexing (TDM). In those embodiments where the optical fiber pressure sensors 32 are not connected individually to the instrumentation, the sensors 32 of a sensing array 24,26 may be connected to one another in series or parallel. The optical signals produced by the sensing arrays 24,26 provide information relating to the fluid flow characteristics within the pipe 12 (e.g., local flow disturbances, acoustic wave propagation within the flow, flow pressure magnitude and changes, etc.). Interpretation of the optical signals, which can be done using methods well known in the art, enables the determination of the speed of sound (SOS) of the fluid mixture and the velocity of the fluid flow within the pipe 12. Once the SOS, the flow velocity, the pressure, and the temperature of the mixture are known, other desirable data such as the phase fraction of the constituents within the mixture can be determined. The optical signals from the sensing arrays 24,26 may also be interpreted using the methods disclosed in the following commonly owned co-pending U.S. Patent applications, but are not limited to being used therewith: U.S. Patent application serial nos. 09/105,534 ("Fluid Parameter Measurement in Pipes Using Acoustic Pressures" filed June 26, 1998), serial no. 09/344,070 ("Measurement of Propagating Acoustic Waves in Compliant Pipes", filed 25 June 1999), serial no. 09/344,069 ("Displacement Based Pressure Sensor Measuring Unsteady Pressure in a Pipe" filed 25 June 1999), serial no. 09/344,094 ("Fluid Parameter Measurement in Pipes Using Acoustic Pressures" filed 25 June 1999), and serial no. 09/344,093 ("Non-Intrusive Fiber Optic Pressure Sensor for Measuring Unsteady Pressures within a Pipe" filed 25 June 1999), all of which are hereby incorporated by reference. FIG.2 shows an exemplary embodiment of the present

invention wherein the SOS sensing array 24 and the flow velocity sensing array 26 are positioned adjacent one another on a common length of pipe 12. Further details of this embodiment are provided below. FIGS. 3-5 diagrammatically illustrate sensing array embodiments and attributes that can be used with either or both sensing arrays 24,26.

To avoid interference from outside sources and to protect from the harsh environment within the well, the sensing arrays 24,26 are enclosed within a housing 28 that is attached to an exterior surface of the pipe section 12. The housing 28 includes an outer sleeve 34 extending between a pair of bosses 36. The fiber optic cable(s) 30 that extends between the flow meter 22 and the instrumentation passes through a sealable port 38 in one or both bosses 36 and connects with the sensing arrays 24,26. Outside the housing 28, the sensor cable 30 is housed in a protective conduit 40 that is attached to the pipe 12. In the preferred embodiment, the housing 28 and the pipe 12 together form a pressure vessel. The pressure within the pressure vessel may be greater than or less than the ambient pressure within the annulus 18 between the casing 14 and the pipe 12. In other embodiments, the housing 28 is sealed to protect the sensing arrays 24,26, but does not act as a pressure vessel. In all embodiments, the size and structure of the housing 28 are chosen to withstand the pressure gradients present in the well environment, to accommodate the size of the sensing arrays 24,26, and to allow the sensing arrays 24,26 to be positioned a distance away from the housing 28 such that heat transfer via the pipe 12 and/or the housing 28 is non-disabling for the application at hand. In a preferred embodiment, the housing 28 is filled with a gas such as, but not limited to, air, nitrogen, argon, etc. The gaseous environment within the housing 28 advantageously acts as an acoustic isolator that helps reduce pressure wave interference that might otherwise travel into the housing 28 from the annulus 18 and undesirably influence the sensing arrays 24,26. The gaseous environment also thermally insulates the sensing arrays 24,26.

In some applications, there is advantage in placing a plurality of bumpers within the housing to help maintain separation between the outer sleeve of the housing and the pipe. United States Patent Application serial number [Client

Docket No. CC-0298] discloses bumpers that can be used in this manner and is hereby incorporated by reference.

The pipe section 12 has a compliancy selected to suit the application at hand. The pipe 12 must have sufficient structural integrity to handle the pressure gradient across the pipe 12, and yet must also be able to deflect (i.e., change in circumference) an amount that will yield useful information. The amount the pipe 12 will change in circumference for a given pressure distribution is determined by the thickness of the pipe wall 42 and the physical properties of the pipe material (e.g., modulus of elasticity, etc.). Thus, the thickness of the pipe wall 42 and the pipe material can be chosen to help produce favorable sensor sensitivity for the present apparatus. The characteristics of the pipe section 12 contiguous with each present apparatus may be the same as or different than the characteristics in other sections of the production pipe 12.

The optical pressure sensors 32 used in the SOS and flow velocity sensing arrays 24,26 each include a plurality of optical fiber coils 32. Each coil 32 is wrapped one or more turns around the circumference of the pipe section 12 in a manner that allows the length of the optical fiber within the coil 32 to change in response to a change in the circumference of the pipe 12. If, for example, a pipe 12 can be expected to see a maximum circumferential change of "y", then a one-turn coil will be subject to a maximum potential change in length of "y" (or some known function of "y"). If an optical measurement technique is not sensitive enough to register a change in distance equal to "y", then the coil 32 can be wrapped to include "n" number of turns. The change in fiber length "y" per turn is therefore multiplied by "n" turns, and a change in fiber length great enough to produce a useful signal (i.e., "n • y") is provided. In fact, the same technique can be used to not only provide a minimum useful signal, but also to increase the sensitivity of the sensor 32 and therefore the range of detectable changes in the circumference of the pipe 12. In all cases, the length of the optical fiber in each coil 32 is known and is chosen to produce the sensitivity required to sense the disturbance(s) of interest for that particular sensor. The preferred embodiment, as described above, includes coils 32 wrapped around the circumference of the pipe 12. Alternatively, the optical fiber lengths can be arranged around a portion of the circumference of the pipe 12.

The turns of optical fiber in a sensor 32 are preferably laid next to one another to minimize the axial component of each turn, and thereby keep each turn to a known, constant length. Alternatively, some or all the turns of a coil 32 could be separated from adjacent turns. A coil 32 can consist of a single layer of optical fiber turns, or multiple layers of optical fiber turns depending on the application. The coil 32 of optical fiber in each sensor 32 may be attached to the pipe 12 by a variety of attachment mechanisms including, but not limited to, adhesive, glue, epoxy, or tape. In a preferred embodiment, a tape having an adhesive substance attached to opposite surfaces of a substrate is used. The tape adheres to both the pipe 12 and the fiber and provides a smooth surface on which the fiber can be laid. It is our experience that tape used on a rough surface helps to decrease micro-bend losses within the optical fiber.

In most embodiments, the optical pressure sensors 32 used in the SOS and flow velocity sensing arrays 24,26 further include one or more optical reflective devices 46 disposed between coils 32 that are wavelength tunable. In a preferred embodiment, the optical reflective devices 46 are fiber Bragg Gratings (FBGs). An FBG, as is known, reflects a predetermined wavelength band of light having a central peak reflection wavelength (λb), and passes the remaining wavelengths of the incident light (within a predetermined wavelength range). Accordingly, input light propagates along the cable 30 to the coils 32 and the FBGs reflect particular wavelengths of light back along the cable 30. It is our experience that in most applications there is advantage in placing an isolation pad between each optical reflective device and the outer surface of the pipe to accommodate pipe growth and/or vibrations. United States Patent Application serial number [Client Docket No. CC-0294] discloses such an isolation pad and is hereby incorporated by reference.

In the embodiment of the present invention shown in FIG.3, the sensors 32 are connected in series and a single FBG 46 is used between each of the sensor 32, and each FBG 46 has a common reflection wavelength λ_1. In the embodiment shown in FIG.4, the sensors 32 are connected in series and pairs of FBGs 46 are located along the fiber at each end of each of the sensors 32, respectively. The FBG pairs 46 are used to multiplex the sensed signals to identify the individual sensors 32 from optical return signals. The pair of FBGs

46 on each end of the first sensor 32A have a common reflection wavelength λ_1, and the second pair of FBGs 46 on each end of the second sensor 32B have a common reflection wavelength λ_2, but different from that of the first pair of FBGs 46. Similarly, the FBGs 46 on each end of the third sensor 32C have a common reflection wavelength λ_3, which is different from λ_1,λ_2, and the FBGs 46 on each end of the fourth sensor 32D have a common reflection wavelength λ_4, which is different from $\lambda_1,\lambda_2,\lambda_3$. The sensors 32 within either sensing array 24,26 may alternatively be connected to one another in parallel by using optical couplers (not shown) that are positioned upstream of each sensor 32 and coupled to a common fiber.

Referring to FIGS. 2, 3, and 4, the sensors 32 with the FBGs 46 disposed therebetween may be configured in numerous known ways to precisely measure the fiber length or change in fiber length, such as an interferometric, Fabry Perot, time-of-flight, or other known arrangements. An example of a Fabry Perot technique is described in US Patent. No. 4,950,883 "Fiber Optic Sensor Arrangement Having Reflective Gratings Responsive to Particular Wavelengths", to Glenn. Alternatively, a portion or all of the fiber between the optical reflective device 46 may be doped with a rare earth dopant (such as erbium) to create a tunable fiber laser, examples of which can be found in U.S. Patent Nos. 5,317,576; 5,513,913; and 5,564,832, which are incorporated herein by reference.

Referring to FIG.5, in an alternative embodiment the sensors 32 may also be formed as a purely interferometric sensing array by using sensors 32 without FBGs 46 disposed therebetween. In this embodiment, each sensor 32 is independently connected to the instrumentation at the platform 20 and known interferometric techniques are used to determine the length or change in length of the fiber around the pipe 12 due to pressure variations. U.S. Patent 5,218,197, entitled "Method and Apparatus for the Non-invasive Measurement of Pressure Inside Pipes Using a Fiber Optic Interferometer Sensor", issued to Carroll discloses such a technique. The interferometric wraps may also be multiplexed in a manner similar to that described in Dandridge, et al, "Fiber Optic Sensors for Navy Applications", IEEE, Feb. 1991, or Dandridge, et al, "Multiplexed Interferometric Fiber Sensor Arrays", SPIE, Vol. 1586, 1991, pp.176-183. Other techniques to determine the change in fiber length may also be used. In addition,

reference optical coils (not shown) may be used for certain interferometric approaches and may also be located on or around the pipe 12 but may be designed to be insensitive to pressure variations.

Adjacent sensors 32, within either sensing array 24,26, are spaced apart from each another by a known distance or distances. The sensors 32 in an array are preferably equidistant from one another, but not necessarily. In both sensing arrays 24,26, the spacing between adjacent sensors 32 and the number of sensors 32 reflect the nature of the signal being sensed; i.e., the SOS sensing array 24 utilizes acoustic signals having relatively long wavelengths, and the flow velocity sensing array 26 utilizes local pressure variations within the flow having relatively small coherence length. In relative terms, the sensors 32 in the SOS sensing array 24 are spaced apart from one another substantially further than are the sensors 32 within the flow velocity sensing array 26 because of the intrinsic differences in the signals being sensed. The exact inter-spacing and number of coils 32 in a sensing array 24,26 is application dependent and is a function of parameters such as, but not limited to, the spectra of anticipated acoustic signals and local pressure variations, the anticipated SOS of the fluid constituents, the number of sensors 32, the processing technique used, etc. Examples of signal processing techniques can be found in the following references, which are incorporated herein by reference: H. Krim, M. Viberg, "Two Decades of Array Signal Processing Research - The Parametric Approach", IEEE Signal Processing Magazine, pp.67-94, R. Nielson, "Sonar Signal Processing", Ch. 2, pp.51-59.

FIG.2 shows an exemplary embodiment of the present invention flow meter 22 that can be inserted in-line within a production pipe 12 and disposed at an appropriate position within the well. The flow meter 22 includes a SOS sensing array 24 and a flow velocity sensing array 26 mounted on a section of pipe 12 adjacent one another and enclosed within a housing 28. A fiber optic cable 30 extends through one of the housing bosses 36 and connects to an optical delay line 48. An optical fiber 50, in turn, connects the optical delay line 48 to the SOS sensing device 24. The SOS sensing device 24 includes six (6) sensors 32 located at six predetermined locations (x_1,x_2, x_3, x_4, x_5, x_6) along the pipe 12, where each sensor 32 is separated from adjacent sensors 32 within the SOS sensing array 24 by an axial length increment equal to "Δx". Each sensor is

mounted on a tape that includes adhesive on both faces. A FBG 46 is positioned between the optical delay line 48 and a sensor 32. One FBG 46 is also positioned between and connected to each pair of adjacent sensors 32, such that the optical delay line 48, the FBGs 46, and the sensors 32 in the SOS sensing array 24 are in series with one another. It is preferred, but not required, to skew each FBG 46 between the adjacent sensors 32 to as to minimize the sharpness of the directional changes within the fiber of either sensor 32 or within the FBG 46.

An optical fiber 52 extends from the last sensor 32 in the SOS sensing array 24 over to a first sensor 32 in the adjacent flow velocity sensing array 26. A FBG 46 is disposed in-line between the two devices. The flow velocity sensing array 46 includes four (4) sensors 32 located at predetermined locations (x_7, x_8, x_9, x_{10}) along the pipe 12. Like the SOS sensing array 24, each sensor 32 in the flow velocity sensing array 26 is mounted on tape and is separated from adjacent sensor 32 within the flow velocity sensing array 26 by an axial length increment equal to "Δx". The axial distance Δx separating the sensors 32 in the flow velocity sensing array 26 is, however, substantially shorter than that used in the SOS sensing array 24 because of the difference in the characteristics of the pressure disturbances sought to be measured; i.e., the SOS sensing array 24 senses relatively long wavelength acoustic signals traveling through the fluid flow at the speed of sound, and the flow velocity sensing array 25 senses relatively short coherence length local pressure variations with the fluid flow. One FBG 46 is positioned between and connected to each pair of adjacent sensors 32, such that the FBGs 46 and the sensors 32 in the flow velocity sensing array 26 are in series with one another. Here again, it is preferred to skew each FBG 46 between the adjacent sensors 32 so as to minimize the sharp changes within the fiber of either sensor 32 or within the FBG 46. In some applications, it may be useful to connect an additional optical delay line 48 after the last sensor 32 within the flow velocity sensing array 26.

In a version of the exemplary embodiment of the present invention flow meter 22 shown in FIG.2, the optical delay line(s) 48 are formed by wrapping approximately two hundred and ten meters (210m) of optical fiber around the circumference of a three and one-half inch (3.5") diameter pipe. Each coil of the SOS sensing device 24 is formed by wrapping one hundred and two meters

(102m) of optical fiber around the circumference of the pipe in a single layer. The optical fiber is wrapped using approximately twenty-five grams (25g) of tension on the fiber. Each turn of the coil is separated from adjacent coils by a fifteen micron (15μ) gap. Adjacent coils in the SOS sensing device are spaced approximately eighteen inches (18") apart, center to center. The velocity sensing device is formed in like manner, except that each coil comprises seven layers rather than a single layer, and adjacent coils are spaced approximately one and eight tenths of an inch (1.8") apart, center to center. In both sensing devices, the FBGs are spliced in the section of optical fiber that extends in a helical fashion between adjacent coils, or between a coil and a delay line, etc. Each FBG and the splices that tie the FBG into the optical fiber are laid on an isolator pad.

An embodiment of instrument 100 used to interrogate the sensing arrays 24, 26 of flowmeter 22 of Figure 2 is a two beam interferometer and is best shown with reference to Figure 6. Optical source 102 produces a series of discrete light pulses, either by gating the light on and off or pulsing the drive current of the laser, 104 directed down fiber 106 to a first coupler 108. Coupler 108 splits pulse 104 into two and directs them along two independent paths 110, 112. Path 110 includes a phase modulator device 114 that imparts a phase modulation carrier on the pulse that travels along path 110. Path 112 includes a time delay, shown as a length of coiled optical fiber 116, that provides a known differential time of flight between the two paths 110, 112. It is advantageous to match the differential time of flight between the two paths 110, 112 with the nominal round trip time of flight of the sensor fiber coils 32(a) – 32(j) as will be more fully described herein below. Coupler 118 combines the two pulses 120, 122, a signal pulse and a reference pulse, onto fiber 124. Pulse 122 includes a phase modulation carrier and pulse 120 lags pulse 122 by a period equivalent to the differential time delay between paths 110 and 112. Depending on the exact sensor string design an optional optical amplifier 123 may necessarily be positioned within the fiber string. The two pulses 120, 122 are directed through a directional coupler 126, which may comprise any number of devices such as an optical splitter or an optical circulator as shown in Figure 6, and is further directed into a fiber optic cable 128 to the sensing arrays 24, 26 of flowmeter 22. The pulses 120, 122 reach the sensing arrays 24, 26 wherein they pass through

the various windings of time delay coil 48 and sensor fiber coils 32a- 32j, and optical reflective devices 46a- 46k, shown as FBGs (Fiber Bragg Gratings). As described hereinabove, the gratings 46a – 46k are designed to reflect a small amount of the pulses back up the telemetry cable 128 to the optical circulator 126 and further allow the remainder of the pulses to pass to successive sensor fiber coils and gratings. In the embodiment shown all of the gratings are designed to reflect the same wavelength, λ_1, although gratings written at different wavelengths are also contemplated by the present invention. As will be described more fully herein below, a portion of the pulses 122, 120 is reflected back to the optical circulator by each of the gratings 46a - 46k. Optical circulator 126 directs each of the return signals to photo receiver 130 and onto the demodulator 132.

In the embodiment shown in Figure 6, pulses 120, 122 first go through a time delay loop 48 and then onto the first grating 46(a). Time delay loop 48 is so positioned at the beginning of the flowmeter to provide a method for allowing for non-grating produced reflections of pulses 120, 122 such as those created by connectors 149 or other known reflection producing devices. For instance, if connector 149 creates a small reflection, say –40 dB (0.01%), it will impinge the photo receiver 130 and this reflection, if not sufficiently time separated would corrupt the signal from the gratings 46(a) and 46(b) for interpreting sensor 32(a). Time delay loop 48 is sized to provide sufficient delay to allow the connector 149 induced reflections of pulses 122 and 120 their own time slots before the first, non-interferometric pulse returns. In addition, a similar time delay coil 151 is positioned at the end of the optical fiber string to allow any reflections from the fiber termination 153 to occupy its own slot and thus not corrupt the reflection signals used to interpret sensor 32(j).

In operation, a portion of the first pulse 122 to reach grating 46(a) is reflected back to circulator 126 first and arrives at photo receiver 130 first, and is referred to (for explanation purposes) as the first pulse returning from the first grating. As described herein above, the majority of light from the first pulse 122 passes through the low reflectivity of first grating 46(a) and through the optical fiber of first sensor 32(a) and on to the second grating 46(b). A small amount of the optical power of pulse 122 is reflected by grating 46(b) back through optical cable 128 and onto photo receiver 130 and is referred to as the first pulse

returning from the second grating. The returning first pulse from the second grating arrives at the photo receiver 130 at a time equal to twice the single pass (double-pass) time of flight of the sensor fiber that makes up first sensor 32(a) relative to the first return pulse from the first grating. The time delay of the double-pass is established to a known quantity and is controlled by, among other things, the length of the fiber in the sensor loop, the type of fiber, and the wavelength of the optical pulse. The remainder of the optical energy of pulse 122 travels along the optical fiber of flowmeter 22 and encounters gratings 46(c)-46(k) and sensor coils 32(b)-32(j) and reflects back successive return pulses to optical receiver 130 relative to respective gratings and sensor transits. Similarly, pulse 120 is referred to as the second pulse and follows pulse 122 by a time delay equal to the time differential between paths 110 and 116. Pulse 120 encounters gratings 46(a)-46(k) and sensor coils 32(a)-32(j) and reflects back successive return pulses to optical receiver 130 relative to respective gratings and sensor transits at a consistent time lag behind the reflected pulses from first pulse 122. In this manner, two separate pulses are received by the photo receiver 130 from each of the gratings 46(a)-46(k) at a consistent time delay from one another. Because the differential time of flight between the two paths 110, 112 and the time delay of a nominal sensor coil are equivalent the first pulse returning from the second grating and the second pulse returning from the first grating arrive at the photo receiver at the same time creating an optical interference pattern.

According to the present invention, the examination and interpretation over relatively short periods of time of the interference patterns created by the arrival of the various pairs of reflected pulses arising from pulses 120, 122 generated from a series of pulses 104 at the photo receiver 130 enables one to detect signals of interest relating to pressure fluctuations in the pipe as described herein above. Although the present invention does not determine pressure within the pipe pressure fluctuations do indeed influence the sensor coils. The pressure fluctuations, acoustic or local perturbations (or other), shorten, lengthen or otherwise strain the optical fibers that make up the sensor coils 32(a)-32(j) thereby effectively changing the nominal time delay of the sensor fiber coils and causing a commensurate phase shift between pulse reflections from the pair of gratings that bracket those sensor fiber coils. For each initiation of pulse 104

from optical source 102 the photo receiver 130 receives a pair of reflected pulses, one each from pulses 122 and 120, from each of the gratings 46(a)-46(k). These pulses are then interpreted by demodulator 132 to derive information about the pressure fluctuations in the pipe in the form of a phase shift between the interfering pulses for each pulse 104 generated. In practice, the optical interference is converted to electrical signals by known methods by way of the square law photo detector, and the phase shifts induced into pulse 122 by straining of the sensor fiber coils 32(a) – 32(j) are extracted by the demodulator 132 in a meaningful (i.e. electronic signal) way.

In operation, and as best shown with reference to Figure 7, the present invention examines the times at which the first and second reflected pairs of pulses 120, 122 impinge upon the photo-receiver 130 in the following manner. The arrival of the first pulse reflection for the grating 46(a)is depicted as 160 and is defined to be time t_0, and as described herein the first pulse reflection from the grating 46(b)is depicted as 164 and returns at $t = t_0 + 2t_{coil(a)}$, where $2t_{coil(a)}$ is the double-pass time of sensor coil 32(a). In this embodiment $t_{delay} \sim= 2t_{coil(a)}$ so the first pulse reflecting from the grating 46(b) returns at $t \sim= t_0 + t_{delay}$. The arrival of the second pulse reflecting from grating 46(a)is depicted as 162 at photo receiver 130 occurs at $t = t_0 + t_{delay}$, where t_{delay} is the time delay of the difference between path 110 and path 112. Similarly, the second pulse reflecting from grating 46(b)is depicted as 166 and returns to photo receiver 130 at $t = t_0 + t_{delay} + 2t_{coil(a)}$. Figure 8 shows the intensity of the reflected signals as a function of time. It is important to note that during the time from $t = t_0$ until $t = t_0 + t_{delay}$, only one pulse reflection depicted as 180 is impinging upon photo-receiver 130 and no optical interference takes place. From $t \sim= t_0 + t_{delay}$ until $t \sim= t_0 + t_{delay} + 2t_{coil(a)}$, two pulses, the first pulse 122 reflecting from grating 46(b) (depicted as 164 in Figure 7) and the second pulse 120 reflecting from grating 46(a) (depicted as 162 in Figure 7), are present at the photo-receiver and optical interference does take place. The interference pattern is primarily influenced by the phase modulation carrier imparted to pulse 122 by phase modulator device 114 under the control of the interrogation electronics and the signal of interest imparted by the sensor fiber coil 32(a) which relates to the pressure induced strains in the sensor fiber coil 32(a) and is depicted as arrow 184 as the intensity may increase

or decrease depending on the interference (constructive or destructive). The strain in the sensor fiber coils 32(a) – 32(j) produces a phase shift in the returning first pulses 122 relative to the returning second pulses 120 for each sensor in a similar manner. The phase modulation imparted onto pulse 122 and the subsequent demodulation by demodulator 132 is then used to extract a linear representation of the phase shift imparted upon the returning first pulse 122 by sensor fiber coil 32(a), which in turn was caused by pressure fluctuations in the pipe for instance, using one of many well-known techniques such as phase generated carrier or active or passive homodyne. In one embodiment of the present invention a phase modulation scheme is employed through the use of a demodulator incorporated into instrument 100 manufactured by Optiphase, Inc. of Van Nuys, CA. Note that the phase carrier modulation can be imparted to the returning second pulse 120 with similar effect.

The present invention uses the analysis described above to interrogate the remaining sensors by analyzing the interference pattern for the interfering pairs of reflected pulses from pulses 120, 122. For instance and as best shown with reference to Figure 7, the interference pattern for sensor coil 32(b) is analyzed by comparing the phase shift between returning second pulse from grating 46(b) and returning first pulse from grating 46(c) between the time beginning at $t \sim= t_0 + t_{delay} + 2t_{coil(a)}$ until $t \sim= t_0 + t_{delay} + 2t_{coil(a)} + 2t_{coil(b)}$. The intensity of the interference pattern for sensor coil 32(b) is shown as 186 in Figure 8. Similarly, the interference pattern for sensor coil 32(c) is analyzed by comparing the phase shift between returning second pulse from grating 46(c) and returning first pulse from grating 46(d) between the time beginning at $t \sim= t_0 + t_{delay} + 2t_{coil(a)} + 2t_{coil(b)}$ until $t \sim= t_0 + t_{delay} + 2t_{coil(a)} + 2t_{coil(b)} + 2t_{coil(c)}$. Again referring to Figure 8, the intensity of the interference pattern for sensor coil 32(c) is shown as pulse 188. The remaining sensors 32(d) – 32(j) are similarly interrogated. With such an interrogation scheme the present invention is capable of a resolution of between about 0.1 to about 1 mRAD/$\sqrt{Hz}$ and an update rate of about 60 KHz.

The present invention will now be described with reference to a single specific embodiment, however the scope of the present invention is not limited to a single embodiment. It should be understood that any of the features, characteristics, alternatives or modifications described regarding a particular

embodiment herein may also be applied, used, or incorporated with any other embodiment described herein. The optical source 102 of a typical embodiment of instrument 100 and flowmeter 22 is a narrow band source comprising a continuous output DFB laser operating at a nominal wavelength of about 1545 nm with approximately less than a 1 MHz line width. An Integrated Optics Chip (IOC) is used to gate the light on and off to create the pulse 104. In the embodiment described herein the IOC is gated by a pulse generator mechanism to emit 1 μsec pulses 104, roughly every 16 μsec, onto fiber 106 as shown in Figure 6. The path length difference between legs 110 and 112 is sized such that the pulses 120, 122 are 1 μsec apart. In such a configuration the leading edge of pulse 120 abuts the trailing edge of pulse 122. As the pulses 120, 122 exit coupler 118 they enter optical amplifier 123 to boost the optical power of the pulses to approximately 100 mW peak and travel along optical cable 128. A portion of optical cable 128 is typically installed with the production pipe 12 (Figure 1) and comprises a pure silica core and is hardened for such an installation as described in co-pending US Patent Application Serial Number 09/121,468 to Bonja, et al, filed July 23, 1998, titled " Fiber Optic Cable for Use in Harsh Environments", which is incorporated herein by reference. As described hereinabove delay coil 48 comprises approximately two hundred ten meters (210m) of optical fiber and nominally provides slightly more than a 2 μsec double-pass delay to separate the connector 149 reflection (or other) from the reflections of pulses 120, 122 from the gratings 46(a) - 46(k). The Fiber Bragg Gratings 46(a) - 46(k) are tailored to reflect light having a wavelength of about 1545 nm and about a 2 to 4 nm bandwidth. Each of the gratings are written to reflect roughly one-quarter of one percent (.25%) of the total optical power. In the embodiment described the gratings are tailored to increase their specific reflectivity to accommodate for optical losses that occur between grating 46(a)(about .25%) and grating 46(k) (about .45%). Each of the sensor fiber coils 32(a) – 32(j) are wrapped and positioned on a pipe 12 (Figure 2) as described herein above with approximately 102 meters of optical fiber to provide a double-pass delay of 1 μsec each.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and

omissions may be made therein and thereto without departing from the spirit and scope of the present invention.